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Ground Vehicle Systems, Lockheed Missiles & Space Co.

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IN LATE 1969, a potential application for Twister[®]-type vehicles was recognized on the North Slope of Alaska (Fig. 1). Visits to the area indicated that Twister's inherent high-speed capability over rough terrain and its good ride qualities could provide an answer to ground transportation problems that were being encountered by the petroleum industry. Although the Twister testbed configuration was not entirely suitable as a "working" vehicle, it was believed that sufficient operating information could be obtained to develop an overall assessment of its potential in this environment. Three weeks of trials were conducted in March and April 1970, using the Prudhoe Bay facility of the Atlantic Richfield Co. as a base. This paper reviews the accomplishment of that evaluation effort.

OBJECTIVES

Objectives of the evaluation effort were as follows:

1. Determine the range of maximum practical vehicle speeds over a wide variety of conditions—soft, deep snow, hard snow ridges, and glare ice.
2. Evaluate the capabilities and limitations of the Twister testbed configuration for operating in the arctic environment under conditions representative of oil field logistical support and geophysical exploration efforts.

3. Establish the overall effects of the arctic environment and of typical operating conditions upon Twister durability characteristics.

TEST VEHICLE DESCRIPTION

The vehicle under evaluation was the Lockheed Twister testbed (Fig. 2), which is an articulated 8 × 8 vehicle. It is designed to permit faster, safer, and more dependable high-speed movement over a wide variety of terrain. It consists of two bodies joined by a unique pivot yoke permitting three degrees of freedom between them. This articulation, coupled with a high-wheel travel suspension system, minimizes the effect of terrain-induced shock and vibration on the crew. Independent front suspension and sprung rear walking beams, a coordinated Ackerman-yaw steering system, and large, low-pressure, radial-ply tires complete the basic concept. Dual power systems are utilized to achieve the high-speed mobility and acceleration required to exploit this concept fully. Additional information on the design and development of the Twister testbed has been given in another SAE paper (1)*. The basic features of the testbed are summarized in Table 1.

*Numbers in parentheses designate References at end of paper.

ABSTRACT

The Twister testbed was operated on the Alaskan North Slope for three weeks in March and April 1970. Although the testbed configuration was somewhat removed from that required in terms of a "working" vehicle, it was believed that sufficient operating information could be obtained to develop an overall assessment of its potential.

The trials indicated that Twister was capable of running over

terrain typical to the North Slope at speeds three to five times faster than existing commercial vehicles. Twister's ride was substantially better when compared to existing vehicles. Although deep snow occasionally stopped the vehicle, the self-recovery capability permitted the accumulation of 800 miles of test operation, of which 500 miles were cross-country, without any need for assistance by another vehicle.

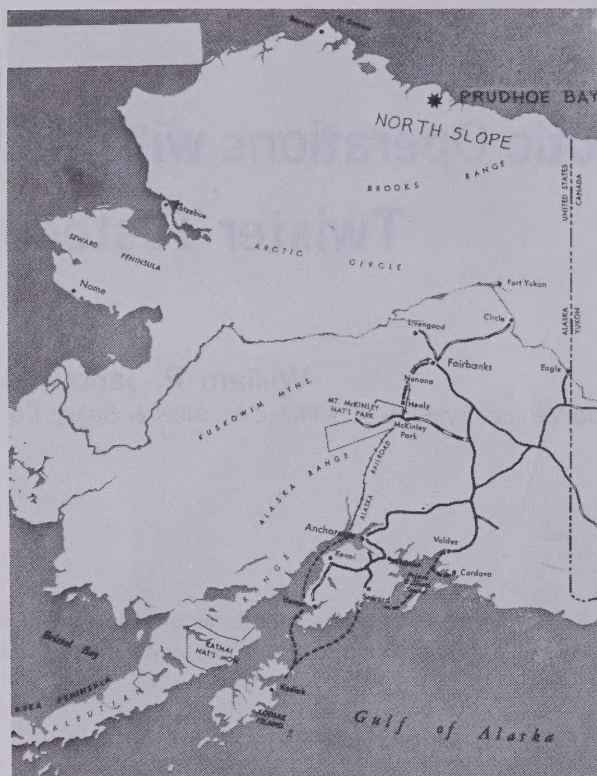


Fig. 1 - State of Alaska



Fig. 2 - Twister testbed—arctic kit installed

TEST VEHICLE MODIFICATIONS

The Twister was modified to cope with the severe arctic environment within the normal constraints of the existing design as well as those presented by program schedules. Operational capabilities at temperatures below -10°F had not been an original vehicle design requirement in 1965. Hence, winterization of the testbed with its air-cooled engines was approached with some trepidation. A combination of past ex-

perience in the design of winter kits for military vehicles and a review of existing literature (2-6) proved to be adequate for successfully accomplishing the conversion. The documents referenced were very helpful in the overall vehicle winterization program; however, published information on winterizing air-cooled engines was somewhat sparse. A decision was therefore made to maintain around-the-clock, warm-engine, power-train compartments in order to ensure ease of starting and operation after overnight or extended shutdown. An additional benefit was a reduced likelihood of problems with other vehicle systems as a result of cold soaking. The subsequent test program proved this conservative approach to be satisfactory. Significant modifications and additions were accomplished in five major areas, and a number of miscellaneous changes were made.

HULL MODIFICATION - Bolted-on covers or adjustable louvers were provided for all hull openings and grills except the axle shaft openings. The various covers and vents could be adjusted and/or removed on site as necessary to provide and maintain the required engine and system operating temperatures.

PERSONNEL CAB - An insulated cab was fabricated and installed over the driver and crew area of the testbed. The cab was constructed of welded aluminum sheets and formed stiffeners. Two doors were provided for easy access, and large tinted safety glass windows were incorporated for maximum visibility. Opening or sliding windows were avoided because of inherent problems related to freezing and sticking. Side air vents were provided for periods of moderate temperature when fresh air would be required. The cab top was painted an international orange color to assist in spotting the vehicle from the air. A rotating beacon on top of the cab further aided in locating the vehicle from on the ground or in the air. Foam was used throughout the cab interior for insulation and noise attenuation.

ENGINE-COOLING AIR AND OIL-COOLING SYSTEMS - The air-cooling intake systems for both engines were modified and ducted so that, by manually moving a louver, the cooling airflow to the engine could be regulated from wide open to fully closed. The louvers were an integral part of the heater system. A three-way valve was installed in the external oil-cooling circuits for both engines to permit bypassing the oil cooler when such action was necessary to maintain the normal engine-oil operating temperature. The front and rear transmission oil-cooler air fans were wired to allow individual actuation by the driver.

HEATER SYSTEM - A 20,000 Btu/hr, 12-V, gasoline-fired air heater was permanently mounted on the right rear fender under a protective enclosure and controlled from within the cab. Electric power was provided by the rear engine battery and fuel by the vehicle gasoline supply. The hot-air ducting configuration permitted two modes of operation—personnel heating and/or engine heating. When the valve was placed on the "Engine Heat" mode, hot air was delivered into the engine-cooling air intake duct for use under rear-engine standby conditions. When the selector valve was turned to the "Personnel Heat" position, hot air was directed to the crew cab. Heated

Table 1 - Vehicle Characteristics (Arctic Kit Installed)

Item	Descriptive Data
Gross vehicle weight, lb	12,880
Payload	Three men, plus survival and vehicle support gear
Length, in.	212
Width, in.	103
Height, in.	95
Ground clearance, in.	16
Turning radius, center of tread, ft.	20
Roll articulation pivot angle, deg	± 30
Pitch articulation pivot angle, deg	35 up; 27 down
Yaw articulation pivot angle, deg	± 22
Angle of approach, deg	90
Angle of departure, deg	80
Engines (2)	Corvair, 6-cyl air-cooled; 120 gross hp (100 net hp) each (est.)
Fuel type and capacity	Premium gasoline, 40-gal capacity, plus 20-gal reserve
Transmissions (2)	Allison, TX-200-2B, torque converter, 6 forward speeds, 1 reverse speed
Tires	16-20, 4-ply, tubeless, steel-belted, radial ply, U. S. Rubber Tire Co.
Differentials	Limited slip
Suspension—Front	Independent
Rear	Independently sprung walking beams
Steering	Coordinated Ackerman steering (front axle wheels) and yaw steering (front body)
Brakes	Internal drum
Maximum highway speed, mph	55
Acceleration, 0-40 mph, sec	17
Gradeability, prepared surface, %	60+
Vertical obstacle capability, in.	30

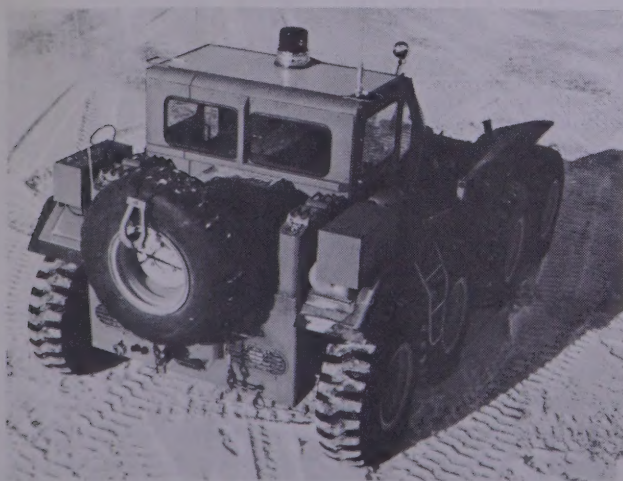


Fig. 3 - Heater installations



Fig. 4 - Front engine heater and front and rear auxiliary power supplies

air was continually directed to the windshield defrost system to ensure adequate defrosting. A second heater, identical to that used with the rear engine, was carried on the vehicle within a portable "suitcase-type" enclosure. During normal vehicle operations, this self-contained package was carried on the left rear fender of the vehicle (Fig. 3). At night, or dur-

ing extended shutdown, the package was installed over the front-engine air inlet (Fig. 4). Fuel and electric power were provided from the front-body systems through quick disconnects. Adequate heat was thereby provided to ensure a warm engine start the following morning. These systems worked so

Table 2 - Chronology of Test Location and Activity

1970 Date	Base Location	General Activities
3/28	ARCO Base	Testbed arrived from Seattle by C-130 Hercules airplane. First experimental runs in Sagavanirktok (Sag) River bed
3/29	ARCO Base	Twister driven to loading dock and storage area. Runs on ice on Prudhoe Bay and ice road to North Prudhoe Bay Well (Fig. 6)
3/30	ARCO Base	Runs out and back to Sag River delta during the morning. Runs on gravel road and ice during afternoon
3/31	ARCO Base	Support to survey work for ARCO Field Coordinator. Round trip to North Prudhoe Bay Well and GSI 150 Camp (Fig. 7)
4/1	ARCO Base to Nora Well	Cross-country run to Nora Well down Sag River bed (Fig. 8)
4/2	Nora Well	Evaluation runs in deep snow to Home Bush Well (round trip)
4/3	Nora Well	Operation in Sag River bed and on deep snow slopes on way to Sagwon (round trip) (Fig. 9)
4/4	Nora Well to ARCO Base	Ice road run back to ARCO base camp. Yaw steering system failure enroute
4/5	ARCO Base	Yaw steering repairs
4/6	ARCO Base	Scheduled maintenance
4/7	ARCO Base	Test runs in the Sag River
4/8	ARCO Base to Western 96 Camp	Cross-country run to camp located off Point Sweeney (Fig. 10)
4/9	Western 96 Camp	Work with camp manager in numerous support tasks. Pulled fuel tanks for drawbar tests. Photographic coverage of cross-country runs by helicopter
4/10	Western 96 Camp to ARCO Base	Cross-country run to ARCO Base camp. Rear suspension failure. Jury-rigged suspension to permit return to ARCO Base
4/11	ARCO Base	Rear suspension repair
4/12	ARCO Base	Rear suspension repairs completed and test runs on Prudhoe Bay
4/13	ARCO Base	Runs on the Prudhoe Bay ice roads
4/14	ARCO Base	Cross-country round trip to GSI 165 camp
4/15	ARCO Base	Runs in Sag River Delta area over snow slopes, in gravel pit, and through eroded islands
4/16	ARCO Base to Anchorage, Alaska	Crew and vehicle departure for Sunnyvale, Calif.

effectively that, on occasion, the heaters were not used at night. The heaters warmed the engines adequately after an overnight cold soak at temperatures to -40 F to permit starting after 15-20 min of heating.

ELECTRICAL SYSTEM - Primary changes to the electrical system, other than the accommodation of new equipment and more equal division of the power load between the front- and the rear-body electrical systems, involved the replacement of some wiring which was inadequate under low-temperature conditions. Before the start of the trip, a sample of each type of wiring used on the Twister was sent to Alaska for evaluation by on-site personnel. Wire which became brittle and cracked when flexed at low temperatures down to -51 F

was replaced. External power supplies (battery chargers) were provided at night and during extended periods of heater operation when the engines were not running. This external source supplied power for the heaters and kept the batteries fully charged and warm.

MISCELLANEOUS CHANGES - These changes included the installation of such on-vehicle equipment as a spare tire, personnel safety and survival equipment, reserve fuel cans, electric slave cables, and the necessary tools and cables to permit self-extraction of the vehicle when immobilized. Throttle and other control cables were replaced with ungreaed cables to prevent sticking at low temperatures. Access holes were provided so that all liquid levels could be checked and refilled

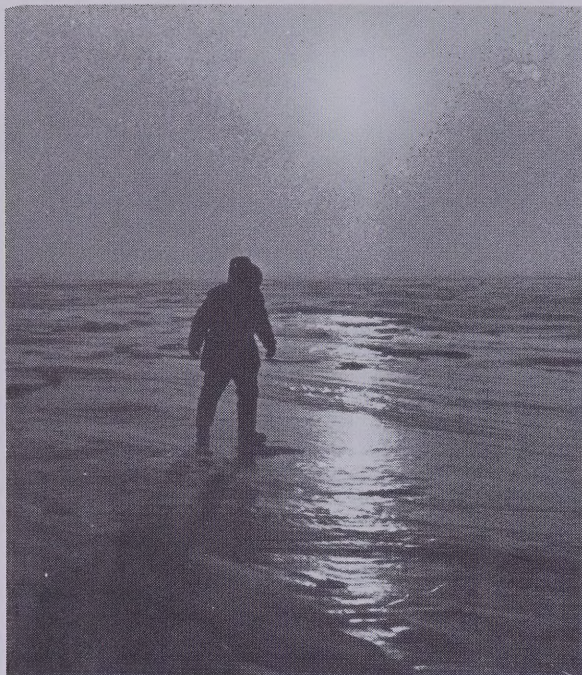


Fig. 6 - Ice on Prudhoe Bay

as necessary without removing any large hull panels. Self-cleaning, open-grid brake and accelerator pedals were installed. The engine crankcase breather lines were routed inside the hulls to prevent plugging by snow. Carburetor air inlets were rerouted to pick up only warm engine-compartment air. Engine starter drives were degreased. Side, rear, and top window frost shields were added to supplement the defrost system which cleaned only the front windshield surfaces. All rubber components (for example, V-belts, hoses, and seals) were checked for low-temperature operating capability. As an added precaution in maintaining clean, water-free gasoline, the fuel tanks were insulated, and easily accessible water drains were provided to permit daily draining of condensates.

FUEL AND LUBRICANTS - Major emphasis was placed upon the selection and application of fluids in the lubrication and fuel systems. The engine oil grade was changed from SAE 30 to SAE 10W. All gear box lubricant was changed from an SAE 90 grade to SAE 75. A friction modifier was added to the SAE 75 lubricant in those units utilizing clutch-type, limited-slip differentials. Bearings, bushings, and splined joints were either repacked or flushed with general-purpose aviation, calcium-soap-thickened, mineral-oil grease, conforming to MIL-G-25537A and with a useful operating temperature range of +250 to -65 F. The speedometer and tachometer drive cables and the distribution cam were regreased with this lubricant.

The same type of automatic transmission fluid (ATF) as that used in more moderate environments was utilized. The SAE 30 oil was removed from the engine-oil-wetted, polyurethane, air-cleaner filter elements, and they were then saturated with ATF. The ATF fluid in the two steering hy-

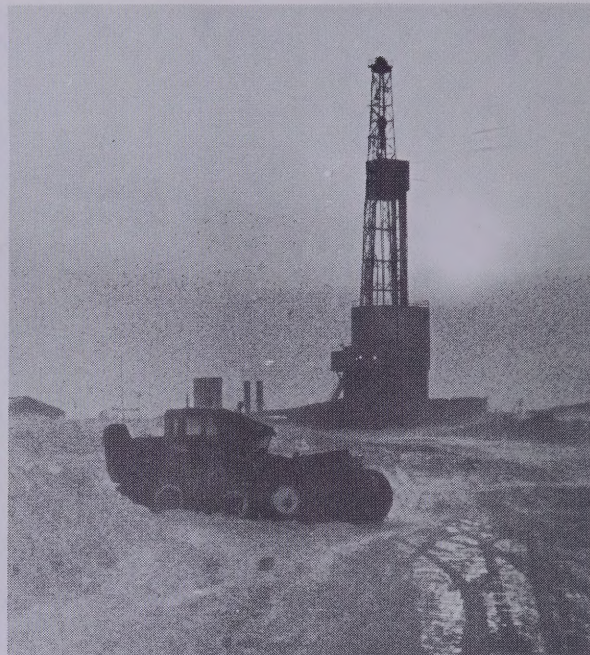


Fig. 7 - North Prudhoe Bay Well



Fig. 8 - Sagavanirktok riverbed

draulic systems was retained. (Problems with the steering system, arising from the utilization of ATF, are discussed later in this paper.) Since the brake fluid conformed to SAE J1703 and was acceptable to -40 F, it was retained.

Special winter-volatility, premium-grade gasoline was provided on site. Fuel deicers and a chamois-lined funnel were carried on board. This permitted the filtering of all fuel taken from drums and the application of deicer with every fill-up.

SCHEDULE OF ACTIVITIES

Table 2 presents a condensed chronology of the test locations (Fig. 5) and of the activities of the testbed and support crew (Figs. 6-10).



Fig. 9 - Snow slopes near Sagwon



Fig. 10 - Mobile camp on Arctic Ocean near Point Sweeney, Alaska

OPERATING DATA

The Twister was on the North Slope for 19 days. During that time, it accumulated approximately 800 test miles, of which over 500 miles were cross-country. Ambient temperatures ranged over this period from -45 to 16 F. Altitude varied from sea level to approximately 500 ft. Fuel consumption varied 1-3 mpg. Maximum cross-country speeds varied, depending upon local conditions and the direction of travel, from 8-25 mph. Average speeds for all cross-country runs were on the order of 15 mph.

TERRAIN CONDITIONS

The North Slope area represents one of the more hostile environments with respect to both man and machine. Ambient temperatures normally vary as low as -60 F, with occasional wind chill factors dropping the temperatures to -100 F or lower. Gale winds under these temperature conditions make work impossible because of the chill factor and their effect on vision. "White-outs"—a condition where a lack of lighting contrast blends the white terrain into a dimensionless environment without any visible horizon—can be a serious hazard to the inexperienced. During the period when work



Fig. 11 - Typical North Slope inland terrain

is possible, the frozen snow represents an ominous although not necessarily immobilizing obstacle. The snow on the flat North Slope tends to blow until a man-made "berm," river bank, tundra hummock, or other projection causes it to drift. On the average, the snow is only about 1 ft deep on the inland flat slope within 30 miles or so of the ocean shore (Fig. 11). Snow conditions are similar on the Arctic Ocean which is frozen for a distance of 75-100 miles from shore. The snow in the flat areas is very hard and is in the form of sharp-edged ridges running northeast to southwest, in line with the prevailing wind. When traversed at right angles, they present a random washboard surface with heights of 1 ft or more. Conventional track vehicle movement is very slow, generally less than 2 mph, unless a bulldozer is used to level the snow ridges in order to form an ice road.

In the Brooks Range and its foothills, the snow is much deeper and presents a more formidable obstacle to vehicular movement. "Sugar snow" is quite prevalent. This snow is very low in moisture content, granular in composition, and generally found under a hard, windblown crust. Penetrating the crust results in a vehicle receiving very little support from the sugar snow; immobilization is often the end result. This deep snow results in substantially increased vehicle rolling resistance, even when flotation tires are used.

The brief summer period presents more favorable operating conditions, but existing land-use laws preclude general operations of ground vehicles due to damage to the fragile tundra surfaces and consequent ecological problems. Only air-cushion or special-purpose, very low ground pressure, wheeled or tracked vehicles appear to have a chance of meeting the existing strict performance requirements for summer operations.

EVALUATION RESULTS

These results are based upon an analysis of Twister performance in the arctic environment and the results of post-test teardown and inspection.

ANALYSIS OF TWISTER TECHNOLOGICAL

FEATURES - An analysis was made of those basic elements of the Twister design which contributed to the overall mobility and travel speed of the vehicle in the arctic environment.

STEERING SYSTEM - In terms of minimum radius and response, the steering system was quite satisfactory, provided the temperature did not fall below about -10°F . Below that temperature, the steering effort increased to the point where, at -38°F , it was difficult to steer the vehicle rapidly because of the viscosity of the automatic transmission fluid used in the steering system. The situation resulted in the driver (at very low ambient temperatures) being unable to negotiate narrow, plowed-ice roads rapidly or to take rapid evasive action to avoid obstacles when moving cross-country at high speeds. Subsequent review of this problem with a petroleum supplier indicated that the problem could be overcome by changing to a more suitable type of arctic hydraulic fluid or by diluting the existing automatic transmission fluid 20-40% with kerosene. Resolution of the stiff steering at low temperatures will enhance the vehicle operational capabilities.

YAW SYSTEM - The yaw capability was the outstanding Twister feature during this arctic operation, although the other features—pitch, roll, and large suspension movements—are important in providing the basic increased speed and improved ride over the arctic terrain. It was the powered yaw feature which permitted the vehicle to self-recover on five separate occasions when immobilized in deep snow. The yaw system, under these conditions, enabled the driver to get the front wheels out of the deep ruts and onto new and firmer snow. This important capability permitted the vehicle to roam at will over the North Slope without ground support. This self-recovery capability also gave the driver and crew a certain reassurance when running in deep snow in remote areas far from assistance. Normally, trips to such locations would involve two or more vehicles for reasons of safety.

ACKERMAN STEERING - It was apparent from operations in the arctic environment that the front-wheel steer angle was greater than necessary. The front tires were observed to "scrub" when making full lock turns. A lesser steer angle would probably have been just as effective in making tight turns; however, the existing angle is still required for operations over more conventional terrain.

PITCH MODE - The pitch mode contributed greatly to the basic vehicle capabilities during travel over the rough snow ridges. The full range of pitch was frequently utilized when operating through snow hummocks, berms at the side of plowed ice roads, and eroded islands in riverbeds (Fig. 12).

WALKING BEAM SUSPENSION - The walking beams were frequently subjected to maximum exposure in the pitch mode when operating under severe ice and snow conditions (Fig. 13). Certainly, a lesser vertical travel or pitching motion is not desirable. An opportunity to optimize the numbers or damping qualities of the shocks for the low-temperature environment was not available. An improved ride might have been obtained by a less viscous shock-absorber fluid.



Fig. 12 - Maximum front-body pitch-down capability

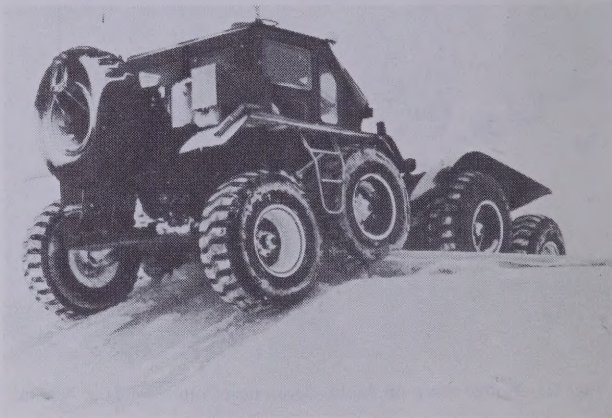


Fig. 13 - Walking beams at maximum pitch capability over ice ridge

ROLL MODE - The roll mode played an important part in keeping the wheels on the ground throughout the entire range of obstacles encountered.

INDEPENDENT FRONT SUSPENSION - The full range of suspension movement was utilized when traveling at high speeds over the low (1 ft or less) washboard snow ridges. These ridges were often quite hard; so hard that, at times, the tires left no marks on the crust. A large-excursion, low-rate suspension system is mandatory for comfort and impact-absorbing qualities. Harshness due to component friction should be minimized.

POWER LOADING - In some instances, the power loading was less than that desirable for the operating conditions. The lack of power was particularly noticeable on roads with grades and in deep snow (sinkage to 16 in.). With an estimated net total output of about 200 hp and an operating gross vehicle weight of approximately 12,880 lb, the vehicle had a power-to-weight ratio of approximately 31 hp/ton. Operating with higher tire pressures on the ice roads would undoubtedly have helped reduce the relatively high tire-rolling resistances encountered. Conversely, being able to operate at a lower tire

pressure when in deep snow would have reduced sinkage and resultant high tire-rolling resistance.

VEHICLE RIDE AND TIRE FLOTATION - Ride and tire flotation for the Twister testbed are two closely interrelated characteristics. The special 16-20, tubeless, low-pressure, radial-ply tire gives both a large and long footprint area and contributes to a good ride due to its inherent impact-absorption properties. (The problems of maintaining air in tires under arctic operating conditions are discussed later in this paper.) Due to this problem, it was necessary to run at pressures above the optimum, that is, above the 40% tire deflection ratio previously used so successfully on the testbed in more moderate climates. Consequently, the vehicle flotation capability was less than that normally available. On five different occasions, when operating under cross-country conditions in areas where wheeled vehicles had never ventured, the vehicle became immobilized in snow sufficiently deep to require extensive hand digging. The snow conditions encountered were a depth of at least 24 in. or more, a hard crust on top, and dry sugar snow underneath. The vehicle would break through the crust and, in view of the insufficient flotation, would dig down through the snow until it "bellied out." The only way to free the vehicle was to dig the snow away from the front and back and under each body, until the testbed had enough clearance to creep out of the ruts by utilizing the powered yaw system to gain new footholds on the sides of the ruts (Fig. 14). On three occasions, the vehicle was backed out of immobilizing conditions; twice, it was driven forward. The nature of the specific terrain dictated the direction that would enable the recovery.

Vehicle ride in the passenger seat (located in line with the walking beam pivot point) was often a limiting factor in maximum speed capability during cross-country runs. Driver ride was never limiting because of the more favorable seat location (about halfway between the rear body walking beam pivot and the front body pitch pivot). There were times when cross-country speeds to 25 mph were possible; at other times, 8-10 mph was the maximum, such as when traversing extremely hard and severe snow ridges at right angles. The speeds attained would undoubtedly have been higher had lower tire operating pressures been possible.

It should be pointed out that the Twister ride was significantly better at high cross-country speeds as compared to the ride in existing commercial tracked vehicles at much lower speeds. Also, the sugar snow which occasionally stopped Twister is also quite difficult for existing low-ground-pressure tracked vehicles to negotiate.

OPERATIONS ON ICE - The entire North Slope area is dotted with frozen lakes and rivers varying from 2-15 ft or more in depth. During the winter months, these bodies of water freeze over and offer reasonably level areas for vehicle movement. In addition, they are quite desirable for geophysical mobile camp sites since they provide a base permitting easy construction of temporary aircraft runways. There are no large patches of exposed ice because the drifting snow tends to build up on top from several inches to a foot or so in depth.



Fig. 14 - Powered yaw capability being utilized to traverse "sugar snow" area

Vehicle handling was evaluated on the ice in a number of different geographical areas, and moving cross-country on ice did not present a problem to the Twister testbed. As with all vehicles, attempts to accelerate too rapidly or to make tight turns at high speed on ice resulted in some testbed skidding. The application of studs to tires on the front axle did not improve the situation, although it is believed that larger-diameter studs would have a beneficial effect because of their greater area. It is possible that studs will be required should the vehicle be used as a prime mover to pull a trailer over ice. This condition was not evaluated with the testbed due to the lack of on-site stud-installation equipment.

DRAWBAR-PULL TESTS - Three fuel trailers were pulled at the Western 96 Camp to determine their rolling resistance and the drawbar and maneuverability capability of the testbed. The first fuel trailer consisted of four large flotation tires containing 500 gal of fuel in each tire. The estimated gross trailer weight was 13,000 lb. Initial resistance on smooth, hard-packed snow was 1000 lb and increased to 1500 lb over rough snow and small snow ridges. The vehicle was able to tow the container easily and could make minimum radius turns without difficulty.

The second fuel container was an aluminum tank containing about 500 gal of fuel mounted on an unpowered Nodwell track and frame (Fig. 15). The estimated gross trailer weight was 12,000 lb, and the drawbar load varied from 1500-2500 lb. Minimum radius turns were made on both packed and natural snow areas.

A third fuel container mounted on an unpowered Nodwell track and frame was also pulled. The estimated gross trailer weight was 17,000 lb. The drawbar pull was a steady 3500 lb on flat, smooth snow. Attempts to pull the trailer in the rough, natural snow areas resulted in the vehicle spinning out at a maximum steady drawbar pull of 5000 lb. This gave a

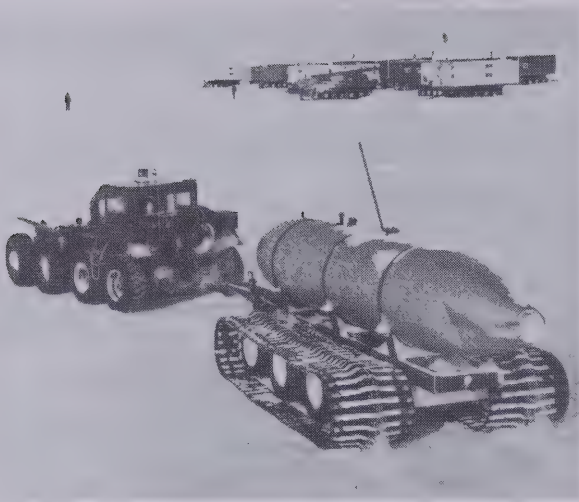


Fig. 15 - Twister towing 12,000-lb fuel trailer

drawbar-pull-to-vehicle weight (DP/W) coefficient of 0.38. This value is slightly less than that developed in similar tests in the Sierra Nevada mountains in 1967 when coefficients of 0.4-0.45 were developed. The difference is probably due to the unfavorable weight balance towards the rear body and to higher internal tire pressures.

VEHICLE WEIGHT DISTRIBUTION - Before the addition of the arctic cab, additional fuel containers, and other gear, the Twister testbed had a weight distribution of approximately 44/56% front to rear, for its gross vehicle weight of 11,650 lb. After the equipment additions for the North Slope operations, the comparable gross vehicle weight was 12,880 lb with a weight distribution of 40/60%, front to rear. Most of the added weight was not only at the rear of the vehicle but was relatively high and raised the rear body c. g. The existing vehicle layout precluded a more favorable weight distribution. Subsequent slope operation on snow was occasionally hampered due to the unfavorable weight bias. Formerly, when operating on steep slopes or in soft, level snow, it had been the practice to shift the rear body transmission into the 1-2 range and the front body into the 3-4 range. This procedure effectively limited the maximum torque to the lighter front-body wheels (as compared to the rear) and resulted in approximately equal wheel slip being developed at all wheels. The new and unfavorable additional weight bias to the rear passed the point where operating in different transmission ranges could compensate for the unequal wheel loading. The problem was quite evident when operating in deep snow or snow-covered slopes with grades up to 30% because the front wheels would "slip out" before the rear wheels began pulling effectively. The necessity for equal wheel weight distribution under dynamic conditions is obvious and has been a major consideration in subsequent vehicle design.

TIRES - Upon arrival on the North Slope, the tire pressure was set at 3 psig front and 5 psig rear (40% deflection ratio). Within the first 10 miles of operation, the right front tire went flat; two other tires went flat while the vehicle was

parked at the garage. Subsequently, the tire pressure was raised to 6 psig all around to reduce downtime due to low or flat tires. Although it was known that these higher pressures would degrade the operation in soft snow and the ride over hard snow, there seemed to be no other choice. These higher pressures undoubtedly contributed to subsequent problems that the vehicle encountered in trying to traverse deep, soft snow.

The tires on the front axle were particularly susceptible to problems stemming from leakage around the beads. This was probably due to high lateral loading and subsequent bead movement. It appeared that all of the tire problems were bead leaks. For a while, the 6-psig pressure all around worked reasonably well; however, several tires went flat each morning, and at least one tire usually had to be changed in the field during a day's run. During the Nora to Sagwon run, two tires went flat, requiring extended running on one flat tire. However, the 12 miles of "run-flat" operation did not damage the tire. In order to alleviate the problems with the front tires, their pressure was raised to 9 psig, and the pressures of the remaining tires were later raised to 8 psig.

All of the tire assemblies were broken down, and extensive rust and snow were found under the tire bead. The four rear four-ply tires were replaced with 6-ply tires after the bead seats were cleaned. The tire pressure was then set at approximately 5 psig. This lower pressure improved the soft snow capability, but random "leakers" required raising the pressure an average of 1 lb to the 6-lb level. The trip was concluded at this pressure range.

At no time was "flat spotting" a problem. Twister could be driven away after an overnight cold soak without encountering excessive "thumping." The tires remained quite flexible throughout the temperature ranges encountered.

Tubes appear to be mandatory equipment for successful operation of low-pressure, radial-ply tires in the winter arctic environment. Most vehicles on the North Slope have gone to tubes to eliminate bead leakage problems. The basic low-aggression tread design was found to be satisfactory, and minor design changes to the wheel rim would have reduced the snow ingestion under the tire bead.

LIMITED-SLIP DIFFERENTIALS - The power train of the Twister testbed was fitted with clutch-type, limited-slip differentials in the No. 1 and 3 axle gearboxes. Positive locking assemblies were fitted in the No. 2 and 4 axle gearboxes. Throughout the trip, operation of the two types of units was observed and compared. The clutch-type units were unsatisfactory because of occasional wheel spin-out when off the ground and wheel stoppage on the ground under low-traction conditions. The positive locking differential appeared to pull far more evenly although some "ratcheting" of the tires was noted. The wheels on the axles with these differentials were not observed to spin free or be independent of the opposite wheel. An effective limited-slip differential is mandatory for snow operations, and having positive locking differentials in all the gearboxes (except possibly the steering axle) would have improved the overall vehicle performance on steep grades and in deep snow.

MECHANICAL PROBLEMS - Only two significant mechanical problems were encountered during the trip. The first was a failure of the yaw-sensing cylinder yoke and mounting bracket bolts. In all probability, the bolts failed because they were loosened by higher than normal wheel reactions (loads) while traveling cross-country. The cylinder yoke subsequently failed due to impact and eccentric loads caused by the loosened bracket. A fix was made to the mounting bracket to ensure that only a shear load was applied to the bolts, and the bolts were safety-wired. Further problems were not encountered. This first failure took place during the return trip from Nora Well to ARCO Base. The powered yaw steering mode was locked out through the existing yaw mode selection switch, and the trip was completed using only the Ackerman portion of the steering system. Steering was somewhat degraded because of excessive side slip of the front tires, and it became obvious that Ackerman steering alone was unsatisfactory for effective vehicle operation in the snow environment. Without yaw steer, it was very difficult and sometimes impossible to make tight turns on hard-packed snow because the front tires were unable to develop sufficient side thrust to turn the vehicle.

The second major failure took place in a weldment at the base of the right-hand walking beam support cylinder, resulting in the beam assembly separating from the vehicle and being retained only by the extended axle shafts and shock absorbers. The failure occurred approximately 10 miles from base during the return trip from the Western 96 Camp at Pt. Sweeney. The vehicle was traversing closely spaced, hard-snow ridges that were 1 ft or more in height. It was necessary to have chains brought out to the vehicle, and the broken walking beam was temporarily chained back into position. Support was applied to hold the walking beam up, and cross chains between the two beams held the failed beam against the side of the body. The balance of the trip was made cross-country without incident. The broken weld was rewelded, and further problems in this area were not encountered.

Both of these failures took place in testbed components that have been eliminated from subsequent Twister designs. These occurrences emphasize the importance of component and system reliability, which can only be really appreciated in relation to being in a vehicle in the arctic wasteland many miles away from any source of support or aid. Every body creak and every off-tune engine exhaust note becomes a matter for concern. A component failure can result in a disabled vehicle and great danger to the occupants because of the extremely adverse environmental conditions. As is always the case where conditions are extreme, there is no reason to substitute vehicle performance for either reliability or maintainability. Fortunately, it was possible to handle the two mechanical failures and five immobilizations encountered in the field, and the vehicle always managed to return to base under its own power.

SUMMARY OF ANALYSIS RESULTS - None of the deficiencies observed are fundamental to the Twister concept, and a reliable solution has since been developed for each problem. Operation of the testbed proved that a vehicle with the right combination of articulation, suspension, and tire character-

istics can operate faster than track vehicles in areas for which wheeled vehicles were previously considered unsuitable or inadequate.

TEARDOWN AND INSPECTION

Following the return of the testbed to California, a complete vehicle teardown was made to perform an inspection of all systems and components. The results of the inspection are summarized by major vehicle systems in the following paragraphs.

POWER TRAIN - The only significant problem in the power train was the cracking of three ring gears in the differential assemblies. Because of space limitations, larger-diameter and stronger ring gears cannot be installed on the testbed.

ENGINE - Both engines were in reasonably good condition; however, the rear powerplant had accumulated greater mileage due to earlier installation and was replaced as a precautionary measure. The lubrication problems normally encountered in cold weather operations were avoided through use of external engine heaters installed before start of the trip.

SUSPENSION - New problems were not encountered in the suspension system. The repair made to the right-hand walking beam while the vehicle was on the North Slope was rechecked and found to be adequate. The front-body suspension arm assemblies and bushings were found to be in very good condition.

ARTICULATION SYSTEM - Only the roll bushings had to be replaced; they had been in use since initial assembly of the vehicle in 1965.

TIRES - The cold weather environment did not have any adverse effect upon the tires. It was necessary, however, to clean out contaminants embedded by the ingestion of snow and mud under the tire bead seats.

The arctic environment did not have any significant adverse effects upon the vehicle components. The problems encountered both during the trip and subsequent to it were those that would have been encountered under similar extreme terrain conditions at more moderate temperatures. In all cases, the initial selection of lubricants was adequate to ensure that component failures could not be attributed to improper lubrication.

CONCLUSIONS

The recent trials of the Lockheed Twister testbed have established that the vehicle can operate effectively in the arctic environment under conditions representative of oilfield logistical support and geophysical exploration activities. Operations were conducted over a wide range of off-road terrain typical to the Alaskan North Slope at travel speeds three to five times faster than existing commercial vehicles. Even at these higher speeds, the crew ride was substantially better when compared to that of existing vehicles. Vehicle durability was considered good, considering the mileage accumulated and the terrain encountered.

The vehicle did not have to be "recovered" even once dur-

ing the evaluation program. Its inherent self-recovery capability permitted wideranging trips into remote areas never before traversed by wheeled vehicles. The Twister overall performance, as witnessed over the period by a wide variety of petroleum industry personnel, was considered to be impressive. Its performance substantially exceeded that of commercially available equipment now used on the North Slope.

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